

# PEDESTRIAN SAFETY UPPER LEGFORM BUMPER IMPACT SIMULATION

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## ABSTRACT

There is increasing concern with the growing number of pedestrians struck by motor vehicles. Honda is actively researching systems to reduce the level of injuries sustained during these collisions. This paper addresses vehicles with bumpers at a pedestrian's thigh height, such as vans and sport utility vehicles. The goal of this research was to predict upper legform forces due to bumper impacts and analyze bumper system concepts for minimizing these forces.

This research was performed through MADYMO simulations of an upper legform impacting a vehicle's bumper system. These simulations facilitated detailed evaluation of this complex impact event and rapid analysis of designs prior to the construction of prototype components. Initial activity examined a traditional bumper system for which test data was available. This provided a baseline simulation for correlation of the computer model. Performance of various pedestrian friendly concepts was examined until a design that met the performance targets was achieved. This design utilizes a deformable steel member attached to the main bumper beam. This deformable steel member absorbs the impact energy, thereby reducing the peak forces on the upper legform.

## INTRODUCTION

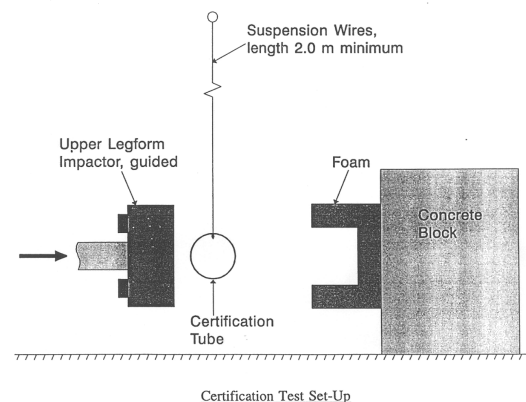
In 1997, 77,000 pedestrians were injured by motor vehicles (1). Honda is actively researching systems to reduce the level of injuries sustained during these collisions. The research for this paper applies to vehicles with bumpers at a pedestrian's thigh height, such as vans and sport utility vehicles. Therefore, an upper legform to bumper impact was analyzed, with the goal of designing a bumper system that reduces the peak forces on the upper legform in this test.

The upper legform is a steel cylinder wrapped by rubber skin wrapped foam, and attached to a weighted rear member at both ends through load cells. The rear member is connected to a hydraulic ram through a torque limiting revolute joint. Strain gauges on the backside of the cylinder are used to measure the bending moments on the cylinder.

The Honda pedestrian friendly bumper design criterion is to limit the peak total force in an upper legform bumper impact test to 7500 N. The total force is the sum of the upper and lower load cell forces. There is also a maximum allowable bending moment for this same test, but typically this is achieved when the force limit is satisfied. There is no limitation on legform acceleration, but this is related to the force.

## BASELINE SIMULATIONS

The upper legform model from TNO's database was used as a starting point for the simulation of the upper legform to bumper impacts. The model consists of a combination of rigid bodies connected by joints, and finite elements modeling the deformable components. In the actual apparatus, load cells measure the upper and lower forces between the legform section and the rear member. The corresponding joint forces are measured in the model. Finite elements represent the front member and the foam surrounding it. The foam is typically difficult to model, due to its high rate dependency. However, TNO's legform model includes the foam material properties, including this rate dependency.

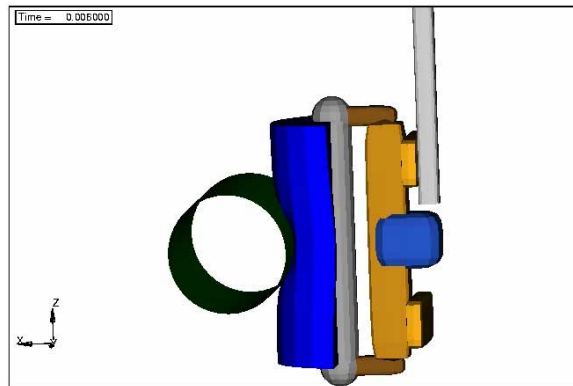


**Figure 1. Certification Test Configuration (2).**

The rear member, impactor ram, extra weights, and connective hardware are modeled as rigid bodies. Their mass and moment of inertia properties were modified to match those of Honda's upper legform. The upper legform's initial velocity was prescribed in the simulation, and the impactor ram was constrained to move along a translational joint parallel to the ground. The pitch motion of the impactor was

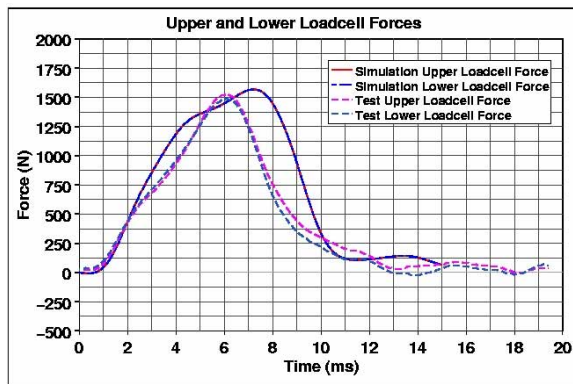
constrained by a torque limiting revolute joint, as in the actual impactor assembly.

A certification test, as depicted in Figure 1, is performed on each upper legform impactor to verify that its performance is within tolerance. Using the MADYMO model, this certification test was simulated. Figure 2 depicts this certification test simulation.



**Figure 2. Certification Test Simulation.**

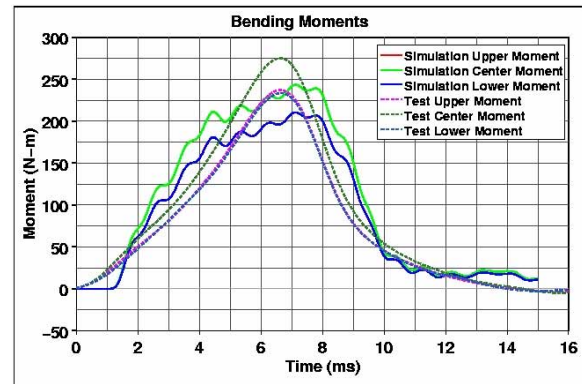
Figures 3 and 4 compare the certification test simulation results with the experimental data.



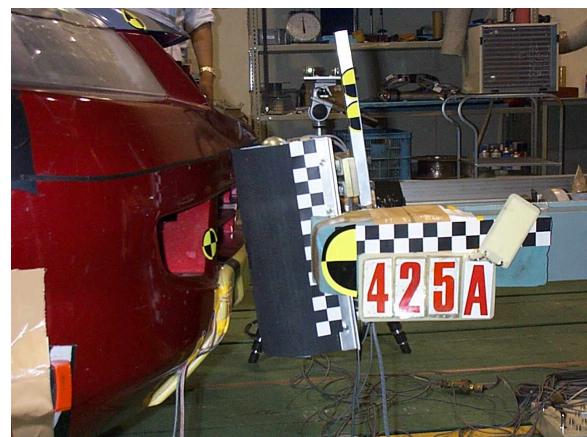
**Figure 3. Certification Test and Simulation Force Comparison.**

The simulation produced similar force and bending moment results, and followed the experimental trends.

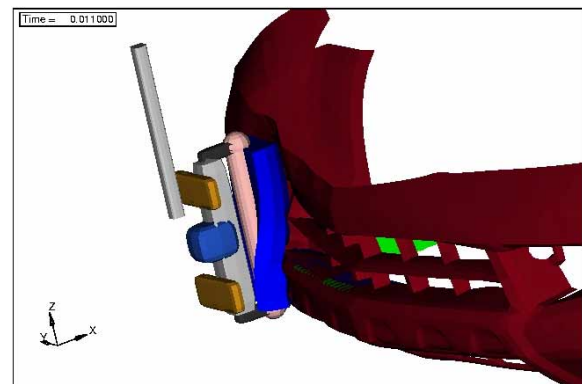
The upper legform model was further validated through simulation of an actual legform bumper impact test. This provided a validation of the finite element bumper system portion of the model, in addition to the upper legform impactor.



**Figure 4. Certification Test and Simulation Bending Moment Comparison.**



**Figure 5. Bumper Impact Test Set-up.**



**Figure 6. Bumper Impact Simulation.**

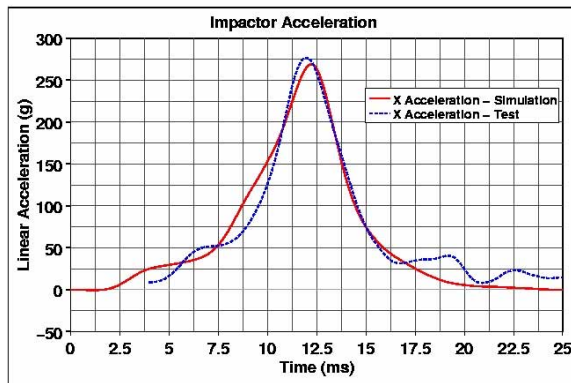
Figure 5 is a picture of the bumper impact test set-up, while Figure 6 depicts the simulation. The vertical aluminum bar visible in Figures 5 and 6 is used to trigger a light trap measuring the impact speed. It was included in the model to account for its mass and moment of inertia properties. The impactor mass was adjusted to the test value. The vehicle's bumper beam and front fascia were modeled with finite elements. The front fascia was included in all the analyses, even though it is not shown in the pictures of the designs.

Table 1 compares the experimental and computer simulation results. The simulation peak acceleration is within 3% of the experimental value, and the correlation of the forces is comparable. While the bending moments do not correlate as closely, this is a more difficult quantity to measure, since the bending moment is calculated from strain gauge measurements.

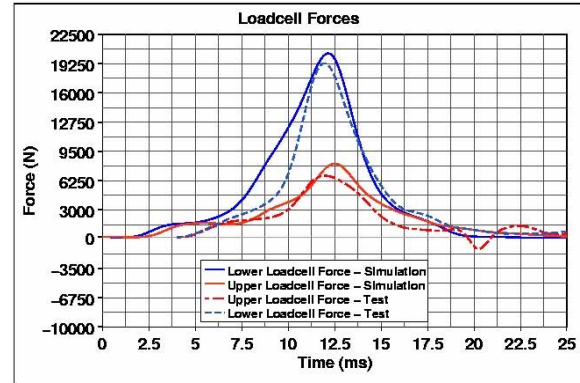
**Table 1.**  
**Baseline Bumper Test and Simulation Results**

	Test	Simulation
G Peak	276.9 g	268.9 g
Upper Force Peak	6800 N	8100 N
Lower Force Peak	19,300 N	20,400 N
Upper Bending Moment	949.1 N-m	1025.8 N-m
Center Bending Moment	1518.9 N-m	1414.5 N-m
Lower Bending Moment	1685.7 N-m	1404.3 N-m

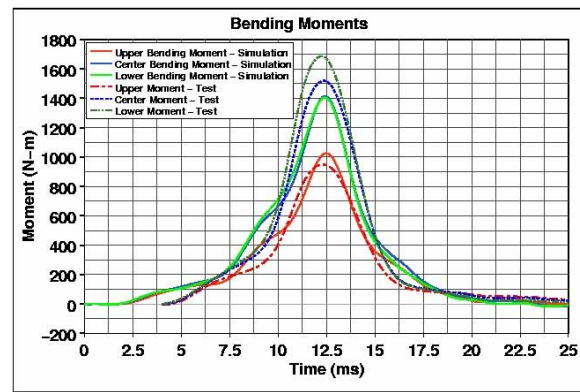
The time histories of the test and simulation results for this bumper impact are shown in Figures 7-9. These graphs also show very good correlation. The accuracy of these simulations justified proceeding with a pedestrian friendly bumper design analysis using the same legform impact model.



**Figure 7. Bumper Impact Test and Simulation Acceleration.**



**Figure 8. Bumper Impact Test and Simulation Forces.**



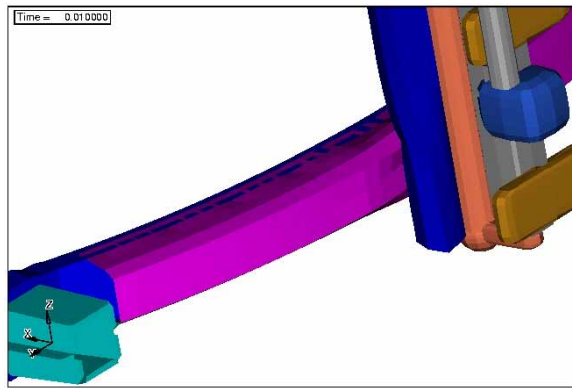
**Figure 9. Bumper Impact Test and Simulation Bending Moments.**

## SIMULATION RESULTS & ANALYSIS

As can be seen from the above results, the baseline bumper system does not meet Honda's pedestrian friendly bumper design criterion of keeping the peak total force less than 7500 N.

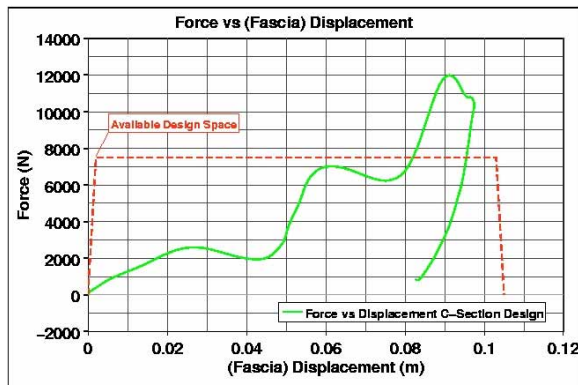
Honda's method for creating a pedestrian friendly bumper system was to attach an energy absorbing section to the front of the primary bumper beam, behind the front fascia. Hereafter this energy dissipating section will be referred to as the nosecone. Several different bumper nosecone designs were initially evaluated. An upper legform impact simulation was performed for each design, using the MADYMO model. Refinements to the designs were made based on these simulations, and subsequently reevaluated.

## C-Section Design



**Figure 10. C-Section Design.**

The first design for a nosecone section connected to the front of the bumper is shown in Figure 10. This was a steel c-section attached to the front of the main bumper beam. Figure 11 shows a plot of the total force of the impactor's load cells vs. the fascia displacement. The simulation fascia displacement was computed as the average of three nodes at the lateral impact location. As Figure 11 shows, the force was initially low, only ramping up near the 7500N maximum at about 60 mm of displacement. Thus, the legform was not sufficiently decelerated at about 80 mm of penetration into the front fascia, at which point it bottomed out against the main bumper beam. This resulted in the high force spike shown in Figure 11 at 90 mm of penetration. Clearly this design did not stay within the maximum force requirement.

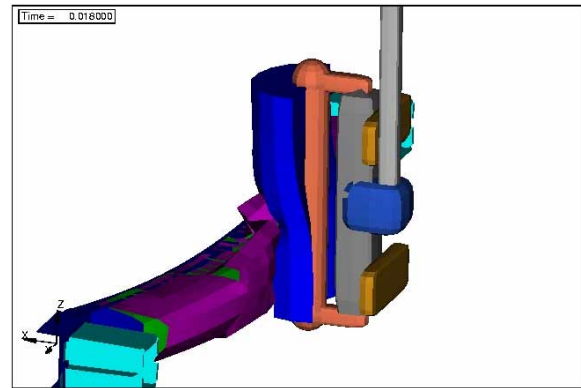


**Figure 11. Analysis of C-Section Design.**

The ideal force versus deflection curve for the energy absorbing section would be a step curve. This would dissipate the most kinetic energy in the shortest distance while not exceeding the maximum force limitation. Thus, the design objective was to achieve a square force versus deflection curve for a bumper

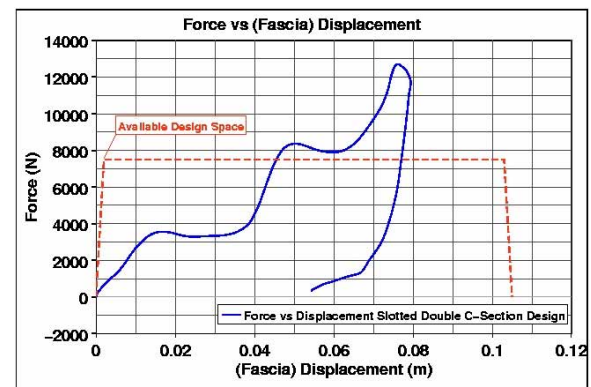
nosecone. Such a curve would fill the “available design space” shown in Figure 11.

## Slotted Double Nosecone Design



**Figure 12. Slotted Double Nosecone Design.**

The next design that was investigated was a slotted double nosecone, which was composed of inner and outer steel c-sections with vertical slots cut in the outer section, as shown in Figure 12. The inner c-section was intended to add a secondary structure to buckle after the outer section had, thereby providing a flatter force vs. crush curve. The vertical slots were intended to prevent the added stiffening of the steel plate due to the tensile loading in the vehicle's lateral direction for large displacements.



**Figure 13. Analysis of Slotted Double Nosecone Design.**

As is evident from Figure 13, this design still does not meet the requirements. The initial force was too low, and the legform still bottomed out against the main bumper beam. Note that the bottoming out occurs sooner due to the extra material of the two nosecone c-sections that are crushed. This was a very undesirable characteristic for this design.



### 3-Step Design

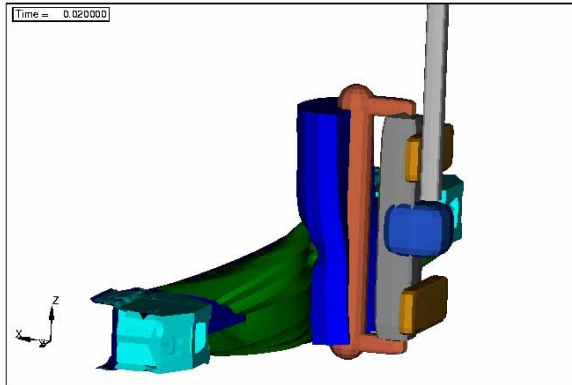


Figure 14. 3-Step Design.

The next design was called the 3-step design because it featured three steps across its cross-section. The steps were intended to produce a square force vs. displacement curve. Ideally, each stepped section would crush sequentially, rather than having a single buckling mode for the entire nosecone, after which the force level drops substantially. The thickness of the 3-step design was varied, in an effort to achieve a force vs. deflection curve that maximized use of the available design space.

Figure 15 shows the force vs. displacement curves for simulation of three different thickness 3-step nosecones. The curves are identical up to 10 mm of displacement because this portion of the curves corresponds to front fascia deformation only. An improved force vs. deflection curve was achieved, but the force level still dropped down around 40 mm of displacement. The 3-step design was not able to meet the performance requirements, having either too much force at low stroke values, or bottoming out the legform against the main bumper beam because it was not decelerated sufficiently when this beam was reached.

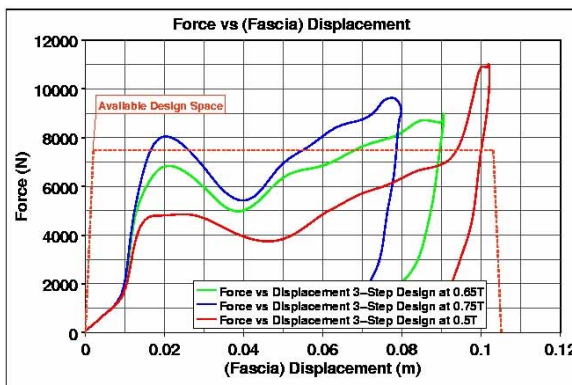


Figure 15: Analysis of 3-Step Design.

### 4-Step Design

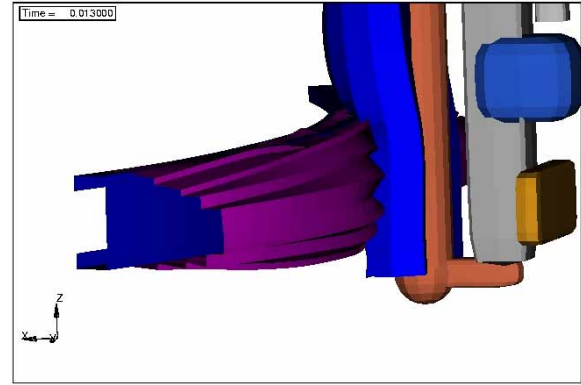


Figure 16. 4-Step Design.

Figure 16 depicts the 4-step design, which was of the same style as the 3-step design, except with four steps rather than three. This was done to investigate the effect of the number of steps on the results. Figure 17 shows this comparison at a thickness of 0.4 mm.

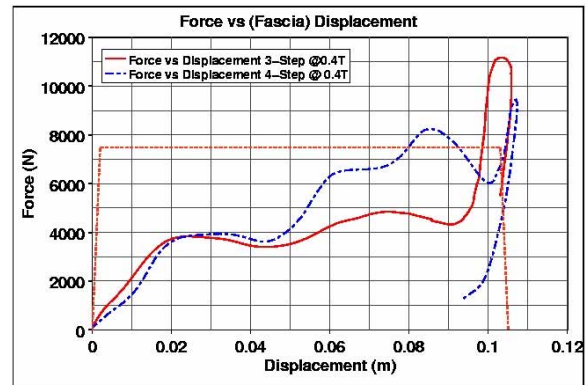


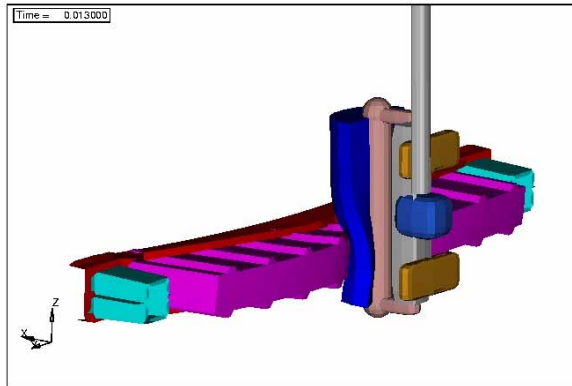
Figure 17. Comparison of 3-Step and 4-Step Designs.

The 3-step design's force vs. deflection curve was closer to a step curve, neglecting the bottoming out portion at the end. It was initially thought that the force vs. deflection curves would simply shift up as nosecone thickness was increased. Thus it was expected that if both force vs. deflection curves were shifted up through a thickness increase, the 3-step design's curve would have more area under the curve.

However, as seen in Figure 15, it was found that the force vs. deflection curve did not simply shift up as nosecone thickness was increased. The reason for this is that the deformation mode changes from a thickness of around 0.5 mm and up. For a thickness of 0.4 mm, the back portion of the nosecone buckled and deformed along with the front portion. As the thickness was increased, the rear portion of the

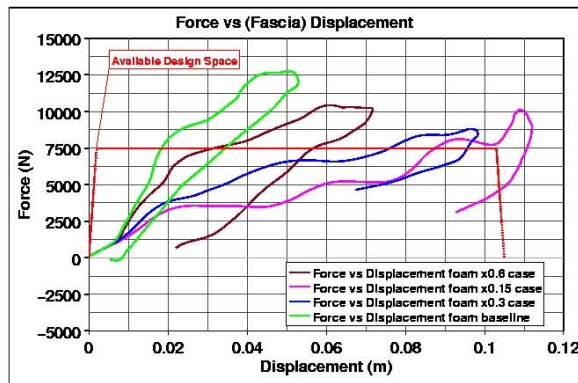
nosecone became strong enough to maintain its shape as the front sections deformed upon initial impact.

## Foam Design



**Figure 18. Foam Design.**

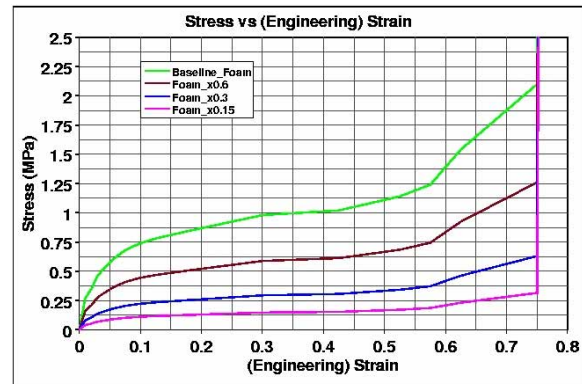
Another design idea was the use of a foam nosecone, as shown in Figure 18. In this design, the main bumper beam section was reversed, thereby cupping the foam as it is crushed. Simulations of foam at varying stiffness levels were performed, with the goal of determining a stiffness that would meet Honda's pedestrian safety requirements. To evaluate foam of differing stiffness, the foam's stress vs. strain curve was scaled, as shown in Figure 20. It is believed that the curve would scale in this manner as the foam density is changed.



**Figure 19. Foam Design Force vs. Displacement.**

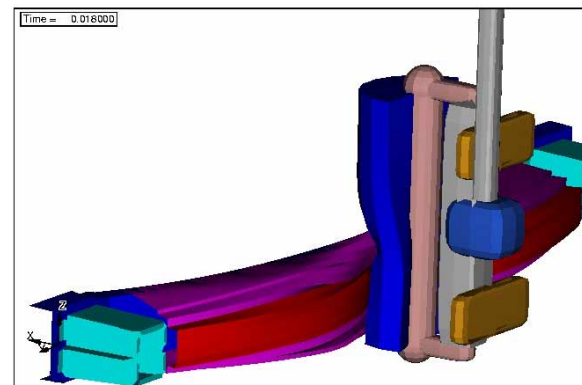
It can be seen in Figure 19 that as the stress vs. strain curve was scaled down, the peak total force on the impactor decreased, and the total stroke increased. However, note that when the foam curve was scaled down to 15% of its original magnitude, the maximum available stroke was exceeded before fully decelerating the impactor. At this point the impactor bottomed out against the bumper beam, and the total force exceeded the 7500 N design limit. Thus, even

before exceeding the available stroke, the force still exceeded the design limit. From this it was determined that the foam design could not be tuned to deliver the desired performance without changing the general shape of the foam's stress vs. strain curve. The availability of foam with such material properties is uncertain. In addition, the cost of the foam design was expected to be higher than that of a steel design. For these reasons the foam design was abandoned.



**Figure 20. Foam Design Stress-Strain Curves.**

## 3-Piece Design



**Figure 21. 3-Piece Design.**

The next design that was analyzed was a 3-piece design. Initially, the stepped designs were only simulated at a thickness of 0.4-0.5 mm. In this range, the peak in the force vs. deflection curve at 20 mm was not as pronounced, as seen in Figures 12 and 15. Therefore, additional stiffness was deemed needed in the initial portion of the force vs. deflection curve. This 3-piece design achieved this additional stiffness by increasing the nosecone center thickness while retaining the smaller top and bottom thickness. The 3-piece design name originates from the fact that the nosecone was composed of three sections welded together.

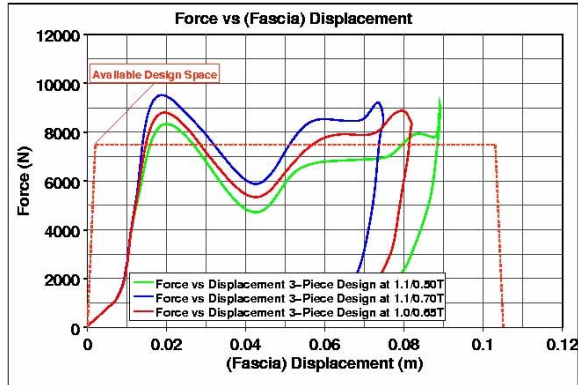


Figure 22. Analysis of 3-Piece Design.

Simulations were performed for several 3-piece design thickness configurations. Figure 21 shows in red the center section that was given a different thickness, with the rest of the nosecone in purple. For the labels in Figure 22, the first number denotes the thickness of the front section of the nosecone (red), and the second number denotes the thickness of the rest (purple). The simulations all demonstrated that this design suffered from the same geometry driven limitation as the 3-step design. As seen in Figure 22, the 3-piece design still exhibited a pronounced dip in its force vs. deflection curve at 40 ms. The 3-piece design was abandoned because it cannot be easily manufactured.

## 2-Piece Design

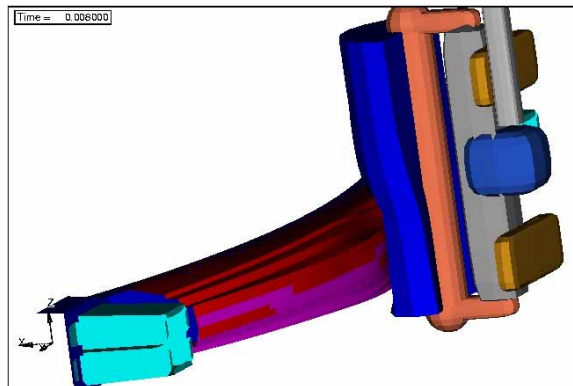


Figure 23. 2-Piece Design.

The 2-piece design had the same shape as the 3-piece design, but was composed of overlapping upper and lower sections that were welded together. This created a thicker middle section like the 3-piece design, but in a manner that could be more easily manufactured.

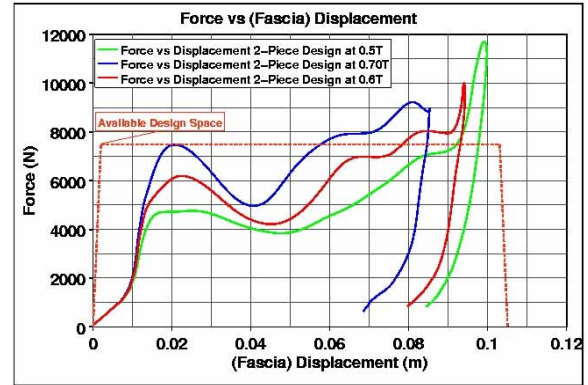


Figure 24: Analysis of 2-Piece Design.

Unfortunately, as is evident from the curves in Figure 24, this design was also unable to meet the desired performance objectives in simulation for any thickness. This design also exhibited a dip in the center of its force vs. deflection curve, making it less efficient than an ideal design. The dip in this curve represents a reduction in the energy dissipated, corresponding to the lost area under the curve. This dip was the only region within the available stroke in which more energy could be dissipated without exceeding 7500 N.

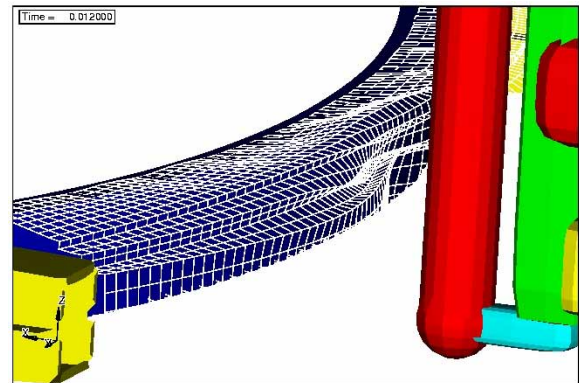
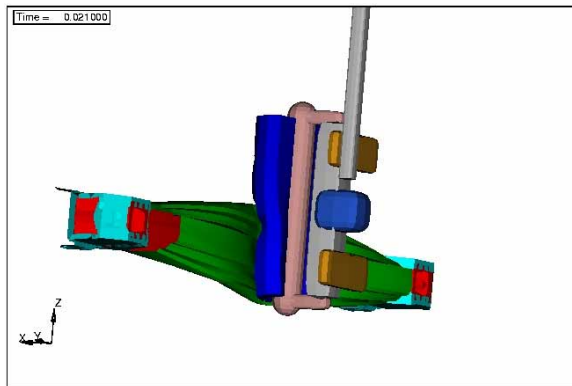


Figure 25. Deformation Mode of 3-Step Design.

Figure 25 depicts the deforming shape of the nosecone for the 3-step design, where the folding over, or bending, of some of the steps can be seen. This corresponds to the dip in the force vs. deflection curve for all of the step type designs. Since the dip is the only area where additional energy can be dissipated, it was determined that the deformation mode creating the dip needed to be eliminated from the nosecone design in order to improve its performance.

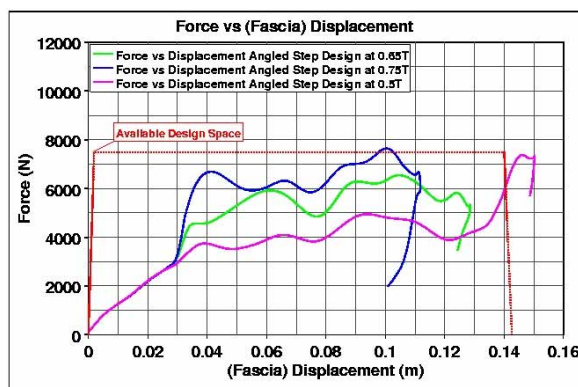
## Angled Step Design



**Figure 26. Angled Step Design.**

The solution to the deformation mode problem was the angled step design shown in Figure 26. For this design, the step angle was changed from the standard 90 to 45 degrees. The sweep of the bumper beam and nosecone was also modified, and the bumper beam longitudinal position was shifted. These changes increased the available stroke at the bumper center by approximately 40 mm.

As seen in Figure 27, this design produced closer to a step curve once the nosecone was contacted. Moreover, at a thickness of 0.65 mm, this angled step design was able to fully decelerate the legform within the now extended available design space, while keeping the maximum force below 7500 N.



**Figure 27. Analysis of Angled Step Design.**

Since this design met Honda's pedestrian friendly bumper system goals, it was selected for further development. Prototype parts were constructed and used in an actual upper legform bumper impact test. The resulting bumper system met the design goals in the actual test.

## CONCLUSIONS

Simulation was used in place of testing for the initial development of a pedestrian friendly bumper system. This simulation effort allowed the feasibility of several different designs to be evaluated early in the design process. Thus, prior to the building and testing of prototype parts, a design direction was chosen and refinements were made to the design. This simulation work greatly accelerated the design process, allowing the testing to be used for confirmation purposes rather than for development work. An angled step design achieved Honda's goals for a pedestrian friendly bumper system.

## ACKNOWLEDGEMENTS

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- (2) European Enhanced Vehicle-safety Committee, "EEVC Working Group 17 Report", December 1998.